DETECTION AND CHARACTERIZATION OF COLD INTERSTELLAR DUST AND PAH EMISSION, FROM *COBE* OBSERVATIONS

E. Dwek[1], R. G. Arendt[2], D. J. Fixsen[2], T. J. Sodroski[3], N. Odegard[2], J. L. Weiland[2], W. T. Reach[4], M. G. Hauser[5], T. Kelsall[1], S. H. Moseley[1], R. F. Silverberg[1], R. A. Shafer[1], J. Ballester[6], D. Bazell[7], and R. Isaacman[7]

ABSTRACT

Using data obtained by the DIRBE instrument on the *COBE* [8] spacecraft, we present the mean $3.5 - 240$ μm spectrum of high latitude dust. Combined with a spectrum obtained by the FIRAS instrument, these data represent the most comprehensive wavelength coverage of dust in the diffuse interstellar medium, spanning the $3.5 - 1000$ μm wavelength regime. At wavelengths shorter than ~ 60 μm the spectrum shows an excess of emission over that expected from dust heated by the local interstellar radiation field and radiating at an equilibrium temperature. The DIRBE data thus extend the observations of this excess, first detected by the IRAS satellite at 25 and 12 μm, to shorter wavelengths. The excess emission arises from very small dust particles undergoing temperature fluctuations. However, the 3.5-to-4.9 μm intensity ratio *cannot* be reproduced by very small silicate or graphite grains. The DIRBE data strongly suggest that the 3.5 - 12 μm emission is produced by carriers of the ubiquitous 3.3, 6.2, 7.7, 8.6, and 11.3 μm solid state emission features that have been detected in a wide variety of astrophysical objects. The cariers of these features have been widely identified with polycyclic aromatic hydrocarbons (PAHs).

Our dust model consists of a mixture of PAH molecules and bare astronomical silicate and graphite grains with optical properties given by Draine & Lee. We obtain

[1]Laboratory for Astronomy and Solar Physics, Code 685, NASA/Goddard Space Flight Center, Greenbelt, MD 20771. eli.dwek@gsfc.nasa.gov

[2] Hughes STX, Code 685.9, NASA/GSFC, Greenbelt, MD 20771

[3] Applied Research Corporation, Code 685, NASA/GSFC, Greenbelt, MD 20771

[4] Institut d'Astrophysique Spatiale, Batiment 121, Universite Paris XI, 91405 Orsay cedex, France

[5]Space Telecsope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

[6]Emporia State University, 1200 Commercial, Emporia, KS 66801

[7] General Science Corporation, Code 902.3, NASA/GSFC, Greenbelt, MD 20771

[8]The National Aeronautics and Space Administration at Goddard Space Flight Center (NASA/GSFC) is responsible for the design, development, and operation of the *Cosmic Background Explorer (COBE)*. Scientific guidance is provided by the COBE Science Working Group. GSFC is also responsible for the development of the analysis software and for the production of mission data sets.

a very good fit to the DIRBE spectrum, deriving the size distribution, abundances relative to the total hydrogen column density, and relative contribution of each dust component to the observed IR emission. At wavelengths above 140 μm the model is dominated by emission from $T \approx 17 - 20$ K graphite, and $15 - 18$ K silicate grains. The model provides a good fit to the FIRAS spectrum in the $140 - 500$ μm wavelength regime, but leaves an excess Galactic emission component at $500 - 1000$ μm. The nature of this component is still unresolved.

We find that (C/H) is equal to (7.3±2.2) 10^{-5} for PAHs, and equal to (2.5±0.8) 10^{-4} for graphite grains, requiring about 20% of the cosmic abundance of carbon to be locked up in PAHs, and about 70% in graphite grains (we adopt $(C/H)_{\odot} = 3.6\ 10^{-4}$). The model also requires all of the available magnesium, silicon, and iron to be locked up in silicates. The power emitted by PAHs is 1.6 10^{-31} W/H $atom$, by graphite grains 3.0 10^{-31} W/H $atom$, and by silicates 1.4 10^{-31} W/H $atom$, adding up to a total infrared intensity of 6.0 10^{-31} W/H $atom$, or ~ 2 $L_{\odot}/M_{\odot}$.

The [C II] 158 μm line emission detected by the FIRAS provides important information on the gas phase abundance of carbon in the diffuse ISM. The 158 μm line arises predominantly from the cold neutral medium (CNM), and shows that for typical CNM densities and temperatures $C^+/H = (0.5 - 1.0)\ 10^{-4}$, which is $\sim 14 - 28\%$ of the cosmic carbon abundance. The remaining carbon abundance in the CNM, which must be locked up in dust, is about equal to that required to provide the observed IR emission, consistent with notion that most ($\gtrsim 75\%$) of this emission arises from the neutral component of the diffuse ISM.

The model provides a good fit to the general interstellar extinction curve. However, at UV wavelengths it predicts a larger extinction. The excess extinction may be the result of the UV properties adopted for the PAHs. If real, the excess UV extinction may be accounted for by changes in the relative abundances of PAHs and carriers of the 2200 Å extinction bump.

Subject headings: interstellar:grains, infrared: radiation - spectrum, ISM: Dust, Extinction

1. INTRODUCTION

A surprising result of the *Infrared Astronomical Satellite (IRAS)* all-sky survey was the detection of a "new" high-latitude diffuse infrared emission component dubbed "cirrus" because its morphology resembled that of filamentary clouds in our own atmosphere (Low et al. 1984). This IR emission component was not entirely new, and had been previously detected through scattered light at optical wavelengths since the 1970's (e.g. de Vaucouleurs & Freeman 1972, Sandage 1976). The surprising aspect of the infrared (IR) observations was their spectra which

displayed an excess of emission at 12 and 25 μm over that expected from dust particles radiating at the equilibrium temperature and heated by the local interstellar radiation field (LISRF). Draine & Anderson (1985) attributed this excess to the effect of temperature fluctuations in small grains. The grain size distribution given by Mathis, Rumple, & Nordsieck (1977; hereafter MRN) was therefore required to be extended to very small grain sizes of ~ 3 Å (Draine & Anderson 1985, Weiland et al. 1986). The cirrus spectrum may, however, arise from the same population of dust particles that give rise to the "unidentified" IR emission features at 3.3, 6.2, 7.7, 8.6, and 11.3 μm. These features were detected in a wide variety of astrophysical objects, reflection nebulae, H II regions, and planetary nebulae (see Cohen et al. 1986 and references therein), and the large-scale emission in the 3.3 μm band was detected by Giard et al. (1988, 1994). However, so far there has been no direct detection of these features in high latitude cirrus clouds, a situation that may change when analysis of data from the ISO and IRTS satellite missions are completed.

The carriers of these features are most commonly identified with a class of molecules called polycyclic aromatic hydrocarbons, or PAHs (Duley & Williams 1981, Léger & Puget 1984, Allamandola et al. 1985, Puget et al. 1985). However, that identification is not unique, and various other compounds such as hydrogenated amorphous carbon (HACs; e.g. Duley 1989, and references therein), or quenched carbonaceous composites (QCCs; e.g. Sakata & Wada 1989, and references therein) have been suggested as alternative carriers of these features. Specifically, Papoular et al. (1989) suggested demineralized coal or vitrinite for the carriers. The optical constants of $10-100$ Å coal grains are such that the grains can maintain *equilibrium* temperatures with near-IR colors in the $500-1000$ K range, provided that they are exposed to radiative fluxes of the order of $10^{-2}-1$ $W\ m^{-2}$ (Guillois et al. 1994). These radiative fluxes are a few orders of magnitude larger than those of the LISRF, suggesting that coals are not likely carriers of the emission features in the diffuse interstellar medium (ISM). Throughout our analysis we will assume that PAHs are the carriers of the unidentified IR emission bands.

Observations of cirrus made by the Diffuse Infrared Background Experiment (DIRBE) and Far Infrared Absolute Spectrophotometer (FIRAS) experiments on board the *Cosmic Background Explorer (COBE)* satellite (Boggess et al. 1992) represent the first spectra of these objects spanning the entire 3.5 to 1000 μm wavelength region. They therefore provide the strongest constraints on the nature of the dust in these regions. Bernard et al. (1994, 1996) presented the DIRBE observed cirrus spectrum for low Galactic latitude ($|b| \leq 10^o$). In this paper we complement their studies by deriving an average high-latitude cirrus spectrum and extending the wavelength coverage to 1000 μm. We also present the spectrum of select individual high-latitude cirrus clouds in order to examine the spectral variations in these objects.

In general, the determination of the cirrus spectrum from the DIRBE maps is complicated as a result of the presence of strong foreground emissions from the interplanetary dust cloud and at 3.5 and 4.9 μm from Galactic stellar emission. In §2 we describe the data set used in the analysis, and briefly reiterate the method developed by Arendt et al. (1996; also presented by Weiland, Arendt, & Sodroski 1996) for the extraction of the cirrus spectrum. The IRAS data provided clear

evidence for the presence of transiently heated dust particles in cirrus clouds (Draine & Anderson 1985). However, as a result of the limited wavelength coverage of the IRAS ($\lambda = 12,\ 25,\ 60$, and 100 μm), the cirrus data could not constrain the *composition* of the very small dust particles. In §3 we show that any extension of the MRN size distribution to very small grains is inconsistent with the DIRBE data. Adopting the PAH model described by Désert, Boulanger, & Puget (1990) to characterize the carriers of the $3.3 - 11.3$ μm features (see Appendix A.2), we show that the DIRBE 3.5 to 25 μm data are consistent with the predicted spectrum from these macro-molecules. A detailed description of the dust model used in this paper is presented in §4, and in Appendix A.1 we describe the method used to calculate the PAHs heat capacities used in this paper. In §5 we describe the fitting procedure, and discuss the uniqueness of the various model parameters derived from fitting the DIRBE observations. We also calculate the abundances of the various dust constituents relative to hydrogen, and calculate the extinction predicted by the model, comparing it to the observed average interstellar extinction curve. The [C II] 158 μm line emission detected by the FIRAS instrument is used to calculate the gas phase abundance of carbon in the diffuse ISM (Appendix A.3), which provides an independent estimate of the amount of carbon required to be locked up in dust. In §6 we compare the far-IR spectrum predicted by the model to the FIRAS observations. The results of our paper are briefly summarized in §7.

2. THE DERIVATION OF THE CIRRUS SPECTRUM

A description of the derivation of the dust spectrum in the general ISM was presented by Weiland, Arendt, & Sodroski (1996), based on the detailed work of Arendt et al. (1996). The data used in the derivation consists of the *COBE*/DIRBE sky maps of emission at $\lambda = 1.25$, 2.2, 3.5, 4.9, 12, 25, 60, 100, 140, and 240 μm (with corresponding bandwidths of 570, 225, 220, 82.1, 135, 41.0, 23.2, 9.74, 6.17, and 4.96, in units of 10^{11} Hz), from which the contributions of interplanetary dust particles and of discrete bright stellar and extragalactic sources and unresolved Galactic starlight has been removed (Kelsall et al. 1996, Arendt et al. 1996). The remaining intensity consists therefore of IR emission from Galactic interstellar dust, and from a diffuse extragalactic background which is assumed to be spatially isotropic.

The spectrum of the ISM, relative to the $I(100\ \mu\text{m})$ intensity, was obtained by deriving the slope of the $I(\lambda)$ versus $I(100\ \mu\text{m})$ correlation for the high latitude regions of the sky that are unaffected by residual interplanetary dust emission. The slope of the correlation is insensitive to any isotropic terms, and the spectrum is therefore free of any extragalactic or any isotropic Galactic emission components. The spectrum was then scaled to the Galactic H I column density by correlating the $I(100\ \mu\text{m})$ intensity to N(H I) over the same regions of the sky. However, by construction, the resulting IR emssion does not originate only from the H I gas, but from all gas phases that correlate with the $I(100\ \mu\text{m})$ intensity.

At wavelengths $\lambda \leq 4.9$ μm the subtraction of the stellar emission component is not sufficiently accurate to bring out the dust emission component in the residual intensity maps. Therefore,

Arendt et al. used near-IR reddening-free colors to identify this component using DIRBE 1.25, 2.2, 3.5, and 4.9 μm data. The procedure is equivalent to identifying dust emission components in color-color plots as the points that are offset from the stellar reddening curve. The method could only be applied to Galactic latitudes with $|b| \leq 25^o$ because of the presence of residual artifacts from the interplanetary dust emission at higher latitudes. As a result there may be a systematic offset between the the 3.5 and 4.9 μm intensities and the rest of the spectrum, if the ratio of the 3.5 or 4.9 to 100 μm intensity is a function of latitude.

The cirrus spectrum at wavelengths longward of 100 μm was derived from the FIRAS Pass 3 data (see Fixsen 1994) from which the microwave background and the dipole have been subtracted, in a fashion similar to that used with the DIRBE data at $\lambda \geq 12$ μm. The first step in this derivation consisted of degrading the Galactic component of the DIRBE 100 μm emission to the FIRAS 7^o beam resolution using the actual FIRAS beam pattern derived from observations of the moon. The full FIRAS high frequency data set was used for $100 < \lambda(\mu m) < 500$, while the combined low frequency data set was used for the $500 - 5000$ μm wavelength region. The spatial correlation with the DIRBE 100 μm intensity map was performed for each of the 167 FIRAS frequency channels. In both frequency regimes, the data were limited to $|b| > 45^o$ and weighted by the FIRAS weights. In the resulting spectrum, the FIRAS intensity matches that of the DIRBE 240, 140, and 100 μm in the respective wavelength bands, confirming the consistency of the data sets and the derivation procedure. Only the $140 - 1000$ μm spectrum of the FIRAS is presented here since the data are too noisy in the remaining frequency channels.

The derived $3.5 - 1000$ μm cirrus spectrum is therefore an *average* spectrum of high-latitude interstellar dust. It represents the average emission from dust integrated over all the non-isotropic ISM components. Dust residing in H II as well as H_2 gas can therefore contribute to the emission. To examine the gas phase dependence of the dust emission we derived the IR spectra of two distinct high latitude clouds. The first cloud (referred herafter as Cloud 1) corresponds to cloud numbers MBM 53, 54, 55 in the catalog of high-latitude molecular cirrus clouds (Magnani, Blitz, & Mundy 1985). It represents a cloud in which the IR emission is dominated by dust residing in the molecular gas and its IR emission is modeled in detail by Dwek, Arendt, Fixsen, & Reach (1996). The second (Cloud 2) was referred to as Cloud A by Low et al. (1984) and modeled by Draine & Anderson (1985). This cloud is notable for having the highest column density of any feature in the $b < -60^o$ H I map of Heiles (1975).

Figure 1 depicts the various cirrus spectra derived in this paper. The diamonds represent the average ISM spectrum, and the spectra of Clouds 1 and 2 are represented by triangles and stars, respectively. The average ISM spectrum is normalized to a value of 0.7 $MJy\ sr^{-1}/N_H(10^{20}\ cm^2)$ at $\lambda = 100$ μm. The other spectra are offset by an arbitrary factor for sake of clarity. Uncertainties in the data are determined by the RMS variation of the $I(\lambda)/I(100\ \mu\mathrm{m})$ colors in different regions of the sky, and equal to 20% (1 σ). We note that the average ISM spectrum presented in the figure is very similar to that derived by Bernard et al. (1994, 1996).

Infrared lines can contribute to the observed emission in the broad DIRBE bands. The most important potential contributor in the diffuse ISM is line emission from [C II] 158 μm in the 140 μm DIRBE band. Our calculations (see §5.2 below) show that this line contributes at most $\sim 2\%$ to the emission in this band. We therefore attribute the observed spectra to thermal emission from interstellar dust.

Table 1 summarizes the various spectra derived in this paper. Also presented in the table are the dust color temperatures determined from the flux ratios in adjacent bands. Refering to the average cirrus spectrum, the 140-to-240 μm and the 60-to-100 μm flux ratios correspond to color temperatures of $\sim$ 19 K, and $\sim$ 23 K, respectively (for a λ^{-2} emissivity law), whereas the 12-to-25 μm and the 3.5-to-4.9 μm flux ratios give color temperatures of $\sim$ 210 K, and $\sim$ 550 K, respectively.

The excess emission at shorter wavelengths has been attributed to the fact that the cirrus emission arises from two distinct populations of dust particles (Draine & Anderson 1985). The first consists of particles radiating at a relatively narrow range of equilibrium temperatures between 16 and 20 K, and the second consists of dust particles small enough to undergo temperature fluctuations. Their contribution to the emission is first noticable at 60 μm, as manifested in the constancy of the 60-to-100 μm Galactic IRAS flux ratio with galactic longitudes (Sodroski et al. 1989, Sodroski et al. 1994), and increases at shorter wavelengths to dominate the emission at wavelengths below 25 μm. Comparison of the spectra depicted in Figure 1, or listed in Table 1, shows variations in the long and short wavelength color temperatures. These variations probably reflect differences in the particle size distributions and/or variations in the intensity or spectrum of the interstellar radiation field. An excellent review of the conditions leading to the stochastic heating of interstellar dust particles and the observational effects of the resulting temperature fluctuations is given by Aannestad (1989).

3. THE DIRBE EVIDENCE FOR THE PRESENCE OF PAHs

The IRAS observations of the diffuse ISM were of limited wavelength coverage and could therefore not constrain the composition of the very small dust particles. Models by Draine & Anderson (1985) and Weiland et al. (1986) could fit the IRAS fluxes by simply extending the size distribution in the interstellar graphite-silicate MRN dust model to very small grain sizes ($a \approx 3$ Å). Subsequent calculations (Guhathakurta & Draine 1989) have shown that graphite and silicate grains with radii less than ~ 4 Å, and ~ 5 Å, respectively evaporate after residing for $\sim 4 \times 10^5$ yrs in the LISRF. The extension to grain sizes below these values is therefore unrealistic in the absense of any replenishing mechanism. Similarly, only PAHs with more than ~ 20 carbon atoms will survive evaporation in the LISRF (Omont 1986).

The DIRBE has more extensive wavelength coverage than the IRAS, and any extension of the standard MRN bare silicate-graphite model to small grain sizes that survive evaporation by

the LISRF is inconsistent with the DIRBE data. However, the DIRBE 3.5 to 25 μm data are consistent with the predicted spectrum from PAHs, if we adopt the model described by Désert, Boulanger, & Puget (1990) to characterize the carriers of the $3.3 - 11.3$ μm features (see Appendix A.2). The "detection" of PAHs with the DIRBE is demonstrated in Figures 2a−2d which compare various observed intensity ratios with calculated in-band DIRBE intensity ratios of individual grain sizes for various grain compositions. Figure 2a shows this comparison for the 3.5-to-4.9 μm intensity ratio (hereafter designated as $R_{3.5/4.9}$). The figure illustrates that no size distribution of silicate or graphite grains can reproduce the observed intensity ratio, since even the smallest grains ($a = 4$ Å, for graphite, and $a = 5$ Å for silicates) have intensity ratios that fall below the observed one. The value of $R_{3.5/4.9}$ is expected to decrease with increasing grain size, since the amount of short wavelength emission depends strongly the maximum temperature reached by the stochastically-heated particles, and for a given radiation field, this temperature decreases with increasing grain size. On the other hand, small PAHs *can* produce larger values of $R_{3.5/4.9}$ because they posses a strong emission feature at 3.3 μm. The figure also gives a good indication of the range of PAH sizes that is required to fit the observed intensity ratio. PAHs are two-dimensional structures, and the relation between the PAH radius and its number of carbon atoms, N_c, is given by $a(\text{Å})=0.913\sqrt{N_c}$ (Désert, Boulanger, & Puget 1990). The figure suggests an average PAH radius of ~ 7 Å, which consists of about 60 carbon atoms. This average PAH size is in reasonable agreement with the value of ~ 90 carbon atoms estimated by Léger, d'Hendecourt, & Défourneau (1989) to comprise a typical PAH molecule giving rise to the observed 3.3 to 11.3 μm color temperature. Figure 2b illustrates the same effect for $R_{12/25}$, the $I(12\mu m)/I(25\mu m)$ intensity ratio. In this case, very small graphite and silicate grains can reproduce the observed intensity ratio, illustrating why a simple extension of the standard MRN dust model to very small grain sizes could explain the IRAS data. Figures 2c and 2d continue this comparison for $R_{60/100}$ and $R_{140/240}$, respectively, both covering wavelength regimes where dust radiating at the equilibrium temperature dominates the emission. This fact is well illustrated in these figures which show that PAHs have significantly higher color temperatures than those implied by the observations. PAHs therefore can not be important contributors to the emission at these wavelengths.

4. A DESCRIPTION OF THE DUST MODEL

The IR flux from any given line of sight is the sum of emissions from dust residing in all the diffuse ISM phases along that line of sight. The specific IR intensity from a population of dust particles characterized by a size distribution $f(a)$ in the radius interval $a_{min} \leq a \leq a_{max}$, and a dust-to-gas mass ratio Z_d, can therefore be written in the most general form as:

$$I(\lambda) = \frac{\mu m_H Z_d}{< m_d >} \times N_H \int_{a_{min}}^{a_{max}} da\ f(a)\ \sigma(a,\lambda) \int dT\ \mathcal{P}(a,T)\ B_\lambda(T) \qquad (1)$$

where μ is the mean atomic weight of the gas in *amu*, $N_H \equiv N_{H\ I} + N_{H\ II} + 2N_{H_2}$ is the *total* H-column density along the line of sight, $< m_d > \equiv \int_{a_{min}}^{a_{max}} da\ f(a) \frac{4\pi}{3} \rho a^3$, is the size-averaged mass

of the dust population, ρ is the mass density of a dust particle, $\sigma(a,\lambda)$ is its cross section at radius a and wavelength λ, $B_\lambda(T)$ is the Planck function, and $\mathcal{P}(a,T)dT$ is the probability that the temperature of a dust particle will be between T and $T+dT$. For dust particles radiating at the equilibrium dust temperature, T_{eq}, the function $\mathcal{P}(a,T)$ is simply a $\delta-$function at $T=T_{eq}$. Implicit in equation (1) is a summation over the various grain compositions. A similar equation applies for PAHs, except that we represent the PAH size distribution as a function of the number of carbon atoms, rather than grain radius.

The dust model used in this paper consists of a mixture of bare silicate and graphite particles, and PAH molecules. An important physical property of the radiating dust particles is their heat capacity. This quantity determines the temperature fluctuations, and hence the function $\mathcal{P}(a,T)$ of the various dust particles. Appendix A.1 describes the heat capacities used for the various grain constituents, with emphasis on PAHs, for which we used the group additive method to determine their value. The relation between $\mathcal{P}(a,T)$ and the various grain parameters and the LISRF has been described by Aanestad (1989). The LISRF used in this paper was taken from Mathis, Mezger, & Panagia (1983). Also summarized in the Appendix are the radiative cross sections used in the model. Graphite and silicate optical properties were calculated from Mie theory using the optical constants of Draine & Lee (1984). Optical properties of the PAH were adopted from the work of Léger, d'Hendecourt, & Défourneau (1989), as summarized by Désert, Boulanger, & Puget (1990).

Given the dust composition and physical and optical properties, a dust model must specify the size distribution and relative abundance of its various constituents. The distributions in grain radii, a, adopted for the various grain material are:

(a) for silicates:

$$f(a) = a^{\gamma} \qquad a_{min} \le a \le a_{max} \tag{2}$$

with $\{a_{min},\ \gamma,\ a_{max}\} = \{0.0050\ \mu\text{m}, -3.5, 0.25\ \mu\text{m}\}$, their MRN value, except that the lower size limit was extended from 0.025 μm, the nominal MRN value, to a lower value of 0.0050 μm;

(b) for graphite:

$$\begin{aligned} f(a) &= a^{\gamma_1} \qquad && a_{min} \le a \le a_b \\ &= a^{\gamma_2} && a_b \le a \le a_{max} \end{aligned} \tag{3}$$

allowing for a break in the slope of the power law at some intermediate radius a_b;

and (c) for PAHs:
The grain size distribution is written as a power law in N_c, the number of carbon atoms in a PAH molecule:

$$f(N_c) = N_c^{\gamma_p} \qquad N_{c1} \le N_c \le N_{c2} \tag{4}$$

The number of carbon atoms in the smallest PAH was fixed at $N_{c1} = 20$ since smaller PAHs will evaporate when exposed to the LISRF (Omont 1986). The number of carbon atoms characterizing

the largest PAH, N_{c2}, and the power law of the PAH size distribution, γ_p, were taken to be free parameters of the model.

We have considered two models using with different constraints on the graphite size distribution. For both models the graphite size distribution is characterized by $\{\gamma_2, a_{max}\} = \{-3.5,\ 0.25\ \mu\mathrm{m}\}$ for radii above a_b. The models differ in their characterization of the distribution of very small graphite grains. The first model (model A) considers the very small graphite grains and the PAHs to be independent populations of particles. We adopt the MRN grain size distribution for this model, but allow a_{min}, the lower limit of the size distribution, to attain values below the nominal MRN value of 0.0050 μm. In this model, $\gamma_1 = \gamma_2 = -3.5$, the MRN value.

In the second model (model B), the graphite size distribution is smoothly joined to that of the PAHs, a distribution one would expect if PAHs were created from the destruction and processing of graphite grains in the ISM. The size of the smallest graphite grain a_{min} was therefore chosen so that the number of carbon atoms in a *spherical* graphite particle of radius a_{min} would equal N_{c2}, the number of carbon atoms in the largest PAH, that is,

$$a_{min}(\mu m) = 1.29 \times 10^{-4}\ N_{c2}^{1/3} \tag{5}$$

The power law of the size distribution in the $\{a_{min}, a_b\}$ size interval was chosen so that $dn(N_c)/dN_c$ is continuous across the PAH-graphite boundary at a_{min}. The value of γ_1 is therefore related to γ_p by

$$\gamma_1 = 3\gamma_p + 2 \tag{6}$$

The constraints on a_{min}(graphite) and N_{c2}, and on γ_1 and γ_p as expressed in equations (5) and (6) are quite arbitrary, but they have the aesthetic virtue of providing a smooth transition from graphite grains to PAHs.

The upper limit of the size distribution of the graphite and silicate grains is uncertain. It cannot be constrained from extinction measurements, since large grains are essentially gray particles. However, the far-IR emission is sensitive to the value of the upper limit, since larger dust particles are colder. Unfortunately, it is difficult to disentangle the effects of grain size from the effects of the intensity of the interstellar radiation field. A higher value of the LISRF will increase the average dust temperature, an effect that can also be achieved by reducing the value of a_{max} by an appropriate value. With this ambiguity in mind, we simply followed previous dust models (e.g. Draine & Anderson 1985), and chose the value of this cutoff to be at $a_{max} =\ 0.25\ \mu$m.

To summarize, the dust model is characterized by 14 parameters: 4 for silicates $\{a_{min},\ \gamma,\ a_{max},\ Z_{sil}\}$; 6 for graphite $\{a_{min}, \gamma_1, a_b, \gamma_2, a_{max},\ Z_{grf}\}$; and 4 for the PAHs $\{N_{c1}, \gamma_p, N_{c2},\ Z_{PAH}\}$. Of these parameters, 8 are fixed, and 6 are allowed to vary in the calculations. Table 2 summarizes the various parameters of the dust model.

5. MODEL RESULTS

5.1. General

To find the dust model that best fits the observed spectrum we mapped out the 3-dimensional χ^2 space spanned by the model parameters: $\{\gamma_p,\ N_{c2},\ a_{min}(\text{graphite})\}$, or $\{\gamma_p,\ N_{c2},\ a_b\}$ depending on the characterization of the graphite grain size distribution (model A or B, respectively). For each value of these 3 parameters, the PAH-to-gas mass ratio, Z_{PAH} was determined from fitting DIRBE 3.5, 4.9, and 12 μm observations with the PAH spectrum. The graphite and silicate dust-to-gas mass ratios, Z_{grf} and Z_{sil}, respectively, were then determined from a χ^2-fit of the model to the residual spectrum.

We expect some correlation between the various dust parameters. For example, N_{c2} and γ_p should be strongly correlated as suggested by Figure 2a. The figure shows that the observed 3.5-to-4.9 μm flux ratio is about equal to that produced by PAHs with ~ 60 carbon atoms. The ratio can however be equally well reproduced by a range of PAH sizes, from $N_{c1} = 20$ to some upper limit N_{c2}. The larger the value of N_{c2} the less these PAHs will contribute to the 3.5 μm emission, and the more the spectrum will need to weighted towards the smaller PAH sizes. Large values of N_{c2} will therefore correspond to steep power laws, i.e. large values of $|\gamma_p|$.

For a given spectrum, grain abundances are primarily determined by their opacities per unit mass. These quantities are relatively insensitive to grain radius, so that the derived abundances are only sensitive to details of the IR spectrum. For example, the abundance of silicates is sensitive to the 140-to-240 μm flux ratio. Exposed to the LISRF, 0.20 μm radius silicate grains attain a lower equilibrium temperature ($T_{eq} \approx 15\ K$) than identically sized graphite particles for which $T_{eq} \approx\ 18\ K$. Smaller values of $R_{140/240}$, will require colder dust to participate in the emission, and will therefore lead to larger values of Z_{sil}.

Table 3 lists the values of the parameters of four models for the average ISM that produced the lowest values of χ^2. For each choice of the graphite grain size distribution (model A or B in Table 2), the four models represent the extreme values of N_{c2} that still provide a good fit to the data. The various models produce almost indistinguishable fluxes with minor differences in the spectra of the various grain constituents. Typical values of N_{c2} are between $\sim$100 and 170. Figure 3 presents the spectrum for dust model A with $N_{c2} = 100$. The figure shows that PAHs dominate the emission at wavelengths $\lambda \lesssim 20\mu$m, whereas stochastically heated graphite grains are important contributors to the emission in the narrow wavelength region of $40 \lesssim \lambda(\mu\text{m}) \lesssim 70$. Graphite and silicate grains contribute about equally to the emission at wavelengths above ~ 300 μm. The main effect of the silicate grains is to broaden the peak of the spectrum around ~ 140 μm. The power emitted by PAHs is 1.6 10^{-31} $W/H\ atom$. Graphite grains emit 3.0 10^{-31} $W/H\ atom$, and silicates emit 1.4 10^{-31} $W/H\ atom$. The total infrared intensity is 6.0 10^{-31} $W/H\ atom$, or 1.9 $L_\odot/M_\odot$, compared to an average value of $\sim$ 3.0 $L_\odot/M_\odot$ found for the inner Galaxy (Sodroski et al. 1994).

PAH size distributions derived here are very similar to that derived by Désert et al. (1990). Translating the results from their Table 2 to parameters used in this paper we get for their model:

$N_{c1} = 19$; $N_{c2} = 170$; $\gamma_p = -1.5$. Similar results were obtained by Siebenmorgen & Krügel (1992) who derived a typical PAH cluster size of 150 carbon atoms.

5.2. Dust and PAH Abundances

Assuming that the H_2 and H^+ contributions to the total H-column density are negligible, we get that the total dust-to-gass mass ratio of the model, Z_{dust}, is equal to 0.0080, consistent with the value of 0.0073 allowed from cosmic abundance considerations (Anders and Grevesse 1989). The small excess may be attributed to the fact that N_H may be larger than $N_{H\ I}$, which would indicate that dust in H I-correlated ionized or molecular medium contributes to the IR emission. The size of the discrepancy seems, however, to indicate that this contribution is small compared to that of the dust residing in the neutral medium. We also note Z_{dust} may be larger than the quoted value, since an additional mass of dust may be required to explain the cold dust component in the FIRAS spectrum (see §6 for more details), or may be present in the ISM but too cold to manifest itself in the current observations.

Similar results are obtained for the carbon abundance required by the model to be in either the PAHs or the graphite grains. The mass fraction of carbon in PAHs is (see Table 3): $Z_{PAH} = 0.00062$, (giving $C/H = 7.3\ 10^{-5}$ for a mean molecular weight $\mu = 1.42$), and for graphite grains $Z_{grf} = 0.0021$, $(C/H = 2.5\ 10^{-4})$. The calculated carbon mass fraction in the solid phase is thus $Z_{C(solid)} = 0.0027$ $(C/H = 3.2\ 10^{-4})$, slightly less than the cosmic abundance value of $Z_C(\odot) = 0.0030$ [$(C/H)_\odot = 3.6\ 10^{-4}$] (Anders and Grevesse 1989).

The "missing" carbon must be in the gas phase and singly ionized (see discussion in Appendix A.3). Its abundance can therefore be derived from the [C II] 158 μm line emission detected by the FIRAS (Wright et al. 1991, Bennett et al. 1994). The $I(158\ \mu m)/I(100\ \mu m)$ line ratio is latitude dependent, and subtracting the dust continuum emission we find a C^+ cooling rate per H-atom of $1.45\ 10^{-33}\ W/H\ atom$ for the high-latitude ISM. This is about half the average value of $2.65\ 10^{-33}\ W/H\ atom$ derived by Bennett et al. (1994) from data that included lower latitude observations. The power in the 158 μm line constitutes about 2% of the total energy received in the DIRBE 140 μm band, and its intensity implies a $[C^+]/[\text{H I}]$ ratio of $\sim (0.5 - 1)\ 10^{-4}$ (see Appendix A.3), which is about equal to $14 - 28\%$ of the cosmic carbon abundance. The *total* carbon to H-atom ratio is therefore $C/H = (3.7 - 4.2)\ 10^{-4}$. This value is consistent with the cosmic abundance limit, confirming previous results that any contribution of the ionized gas to the IR emission is small ($\lesssim 15\%$). Assuming that all the IR emission originates from the H I gas, we get that $\sim 18\%$ of the carbon is locked up in PAHs, $\sim 62\%$ in graphite, and the remaining $\sim$20% is in the gas phase.

The abundance of PAHs needed to account for the IR emission can also be estimated in the following two ways: the first by balancing the energy absorbed by the PAHs from the LISRF to the *observed* emission in the $3.5 - 12$ μm wavelength regime, and independently, by calculating the

PAH optical depth at some representative wavelength dominated by PAH emission.

In the first method the fraction of carbon atoms locked up in PAHs is determined by the ratio of the energy absorbed per C-atoms locked up in PAHs:

$$c\int U_{LISRF}(\lambda)\ \tilde{\sigma}_{PAH}(\lambda)d\lambda = 2.6\ 10^{-27}\ W/(C\ atom) \tag{7}$$

and the observed IR luminosity emitted by the PAHs per H atom:

$$4\pi I_{PAH}/N_H = 1.6\ 10^{-31}\ W/(H\ atom) \tag{8}$$

where in eq. (7), U_{LISRF} is the energy density of the LISRF, and $\tilde{\sigma}_{PAH}$ is the PAH cross section per carbon atom in the molecule. The resulting value is:

$$(C/H)_{PAH} = 6.1\ 10^{-5} \tag{9}$$

similar to the value of $(C/H)_{PAH} = 5.4\ 10^{-5}$ derived by Puget & Léger (1989).

In the second method we calculate the abundance of PAHs required to account for the observed IR emission. These calculations are a simple analytical representation of the detailed model used to derive the results presented in Table 3. We first assume that all the intensity at a given wavelength λ originates from PAHs radiating at an *equilibrium* temperature T_{eq}. The PAH optical depth τ_{PAH} per H column density will then be given by:

$$\frac{\tau_{PAH}(\lambda)}{N_H} = \frac{I(\lambda)/N_H}{B_\lambda(T_{eq})} \tag{10}$$

where $B_\lambda(T)$ is the Planck function. The PAH optical depth can also be expressed as:

$$\tau_{PAH}(\lambda) = N_C\ \tilde{\sigma}_{PAH}(\lambda) \tag{11}$$

where N_C is the column density of carbon atoms locked up in PAHs. The C/H ratio locked up in PAHs is then derived from equations (7) and (8):

$$(C/H)_{PAH} = \frac{I(\lambda)/N_H}{\tilde{\sigma}_{PAH}(\lambda)\ B_\lambda(T_{eq})} \tag{12}$$

We now assume that all the emission in the DIRBE 12 μm is emitted by PAHs. From Table 1 we get that $I_{12\ \mu m}/N_H = 3.16\ 10^{-16}\ Jy\ sr^{-1}cm^{-2}$. PAHs contributing to the emission will be at temperatures of about 425 K, for which $B_{12\ \mu m}(425\ K) = 1.46\ 10^{15}\ Jy\ sr^{-1}$, and the PAH cross section per unit C-atom is $\tilde{\sigma}_{PAH}(12\ \mu m) = 1.4\ 10^{-21}\ cm^2$. The resulting value of $(C/H)_{PAH}$ is $1.5\ 10^{-10}$.

A major assumption made in the derivation of this number is that the PAHs radiate at an equilibrium temperature, when in fact, they are undergoing temperature fluctuations. Therefore, at any given time, the 12 μm observations sample only a fraction of the PAH population, those

that happen to be at temperatures around 425 K. The fraction of "flickering" PAHs is given by $\tau_{cool}(T)/ < \tau_{abs} >$, where $\tau_{cool}(T)$ is the cooling time at temperature T, and $< \tau_{abs} >$ is an average time between photon absorptions. The latter quantity can be simply calculated from:

$$< \tau_{abs} >^{-1} = \int (\frac{\lambda}{h}) U_{LISRF}(\lambda)\ \sigma_{PAH}(\lambda) d\lambda \tag{13}$$

where h is the Planck constant. The PAH cooling time is given by:

$$\tau_{cool}(T)^{-1} = \frac{1}{T} \frac{4 < \tilde{\sigma}_{PAH}(T) > \sigma T^4}{C_{PAH}(T)} \tag{14}$$

where $< \tilde{\sigma}_{PAH}(T) >= 1.4\ 10^{-21}\ cm^2$ is the Planck-averaged value of the PAH cross section per C atom, and $\tilde{C}_{PAH}(T) = 2\ 10^{-16} erg\ K^{-1}$ is the PAH heat capacity per C atom given by eq. (A-4). The resulting cooling time around T = 425 K is $\sim 8\ s$. The absorption time is size dependent. To yield a $(C/H)_{PAH}$ value consistent with the value obtained in eq. (9) the fraction of flickering PAHs must be equal to $1.5\ 10^{-10}/6.1\ 10^{-5} = 2.4\ 10^{-6}$, that is, the average time between photon absorption should be $3.2\ 10^6\ s$. The required PAH size is $N_c \approx 80$, consistent with the typical PAH sizes giving rise to the IR emission.

The derived fraction of carbon locked up in PAHs is about 2 times the value derived by Désert et al. (1990; $C/H = 3\ 10^{-5}$), Verstraete & Léger (1992; $C/H = 4\ 10^{-5}$), or Siebenmorgen & Krügel (1992; $C/H = 3\ 10^{-5}$), but comparable to that estimated by Puget & Léger (1989; $C/H = 5.4\ 10^{-5}$). The abundance of the PAHs is directly proportional to $I_{PAH}(12\ \mu m)/N_H$, and inversely proportional to the wavelength integrated value of $U_{LISRF} \times \tilde{\sigma}_{PAH}$. Differences between the PAH abundance derived here and those derived by Désert et al. can be completely accounted for by the fact that the value of the $\nu I_{PAH}(12\ \mu m)/\nu I(60\ \mu m)$ ratio in our spectrum is larger by a factor of ~ 1.45 than their value. Differences between our PAH abundance determination and that of Verstraete & Léger are due to their use of larger UV-visual cross-sections for the PAHs.

Uncertainties in the derived PAH abundance are dominated by uncertainties in the value of the LISRF, the $I_{PAH}(12\ \mu m)/N_H$ ratio, and the UV-optical cross sections of the PAHs. Total uncertainties in the LISRF are about 15% (Mathis, Mezger, & Panagia 1983). The uncertainty in the ratio of the 12 μm intensity to H-column density ratio is determined by the combined uncertainties in the $I(100\ \mu m)/N_H$ and $I(12\ \mu m)/I(100\ \mu m)$ ratios from which it was derived (Arendt et al. 1996). Uncertainties in each of these quantities are about 10% and 20%, respectively. Combined with the uncertainties in the LISRF, we estimate the uncertainty in the PAH abundance to be about 30%. Uncertainties resulting from those in the UV-optical cross section of the PAHs are harder to evaluate. In our model we have used a value of $\sim 3\ 10^{-18}\ cm^2$/C atom in the 1000 - 3000 Å wavelength range, which is a conservative value according to Allamandola, Tielens, & Barker (1989). Significantly larger UV absorption cross sections will reduce the required PAH abundance. Laboratory data suggest that PAH absorption cross sections in this wavelength region can be larger by about a factor of ten (Joblin, Léger, & Martin 1992). Such large cross sections will make them significant contributers to the UV extinction in this wavelength regime, and potential

carriers of the 2200 Å extinction feature. This possibility will require significant modifications to current dust models, and will not be further considered here. In summary, for the UV-optical cross sections adopted in this paper, the estimated uncertainty in the PAH abundance is about 30%. The same uncertainty applies to the silicate and graphite abundances derived in this paper.

There has recently been an accumulating body of evidence suggesting that the carbon abundance in the gas phase of the local ISM is $(C/H)_{ISM} = (2.25 \pm 0.5)\ 10^{-4}$ (Snow & Witt 1995), about 60% of its solar value. This lower value severely constrains the amount of carbon that can be locked up in dust, leading various authors (Kim & Martin 1996, Mathis 1996) to construct dust models that use up minimal amounts of carbon. The lower C/H ratio in the local ISM is marginally consistent with the lowest value of $\sim 2.7\ 10^{-4}$ present in PAHs, graphite, and in the form of C^+ that is implied by our observations.

5.3. Comparison to the General Interstellar Extinction

An additional constraint on the dust model is provided by the interstellar extinction. It is reasonable to expect that the extinction provided by the dust that fits the average high-latitude ISM emission spectrum will also provide a reasonable fit to the average interstellar extinction curve. Figure 4a compares the extinction from model A with $N_{c2} = 100$ to the average interstellar extinction curve of Mathis (1990). For sake of the comparison, we have multiplied the observed extinction curve, which is normalized to the *total* H column density, by the N_H/N_{HI} ratio, which is equal to ∼1.2 (Savage & Mathis 1979). The figure shows that the predicted extinction is similar to the average interstellar extinction for the H I gas. At wavelengths $\gtrsim$ 20 μm the value of the extinction is uncertain by at least a factor of two (Mathis 1990), so that the model extinction is essentially consistent with the observations.

At UV wavelengths differences between the predicted and the average observed interstellar extinction curve may reflect fundamental uncertainties in dust models, or may suggest a real excess in the high latitude extinction compared to the average Galactic value which is biased towards lower latitudes. The extinction predicted by the model is higher by a factor of ~ 1.3 at $\lambda = 0.125$ μm, increasing to a factor of 2 at 0.1 μm (Figure 4b). The contribution of PAHs to the interstellar extinction is quite uncertain (Verstraete & Léger 1992, Joblin, Léger, & Martin 1992). The UV properties of the PAHs derived by Désert et al. were tailored to fit the observed interstellar extinction curve given in Savage & Mathis (1979). As originally suggested by Greenberg & Chlewicki (1983), the carriers of the 2200 Å extinction feature in the Désert et al. model have an otherwise flat extinction curve, and represent a distinctly different population of particles from those responsible for the rise in the FUV extinction. A similar approach was taken by Siebenmorgen & Krügel (1992), who adopted a small graphite grain component in their dust model, but without the characteristic rise in extinction at UV wavelengths (Fig 1b in their paper), attributing it entirely to PAHs.

The excess of high latitude UV extinction predicted in this paper is therefore directly the result of the enhanced abundance of PAHs derived in our model (a factor of two larger than that derived by Désert et al.) and the adopted PAH UV properties. In our model, the 2200 Å feature is provided by small graphite particles, which also contribute to the rising extinction in the FUV (see also Draine & Lee 1984, Figure 7). Clearly the UV properties of the PAHs should be modified if graphite grains are allowed to contribute to the UV extinction as well. A reduction in the rise of the UV absorptivity of the PAHs will reduce the excess UV extinction exhibited in Figure 4b.

There is some observational evidence suggesting that the UV properties of the PAHs may need to be modified. Boulanger, Prévot, & Gry (1994) have searched for a correlation between the strength of the 12 and 25 μm IRAS emission and UV extinction from select lines of sight through the Chamaeleon molecular cloud complex. They find a correlation between the intensity of the 12 μm emission, which is a measure of the PAH abundance, and the strength of the 2200 Å extinction feature, suggesting a common carrier. Furthermore, they found no correlation between the intensity of the 12 μm emission and the rise in the extinction towards UV wavelengths. These observations suggest that the UV properties of the PAH are quite different from those adopted here.

6. THE FAR-IR SPECTRUM AND THE PRESENCE OF "COLD DUST"

Dust model parameters were solely derived from fitting the DIRBE $3.5 - 240$ μm data, and Figure 3 shows the model spectrum extended to FIRAS wavelengths. The figure shows that even without any attempts to fit the FIRAS data, the model produces a good agreement with the $240 - 500$ μm spectrum. Figure 5 shows the fractional residual emission, defined as $[F(FIRAS) - F(model)]/F(model)$, as a function of wavelength. The residual exhibits a systematic trend in the $100 - 500$ μm wavelength region, consistent with an underestimate in the calculated dust temperatures. To demonstrate the sensitivity of the far-IR spectrum to changes in dust temperatures, we plotted in the figure the fractional residual expected if we had attempted to fit a spectrum with an intrinsic temperature of 17.5 K with a model at 16 K. The figure shows that such a difference could account for the residual emission in the $240 - 500$ μm wavelength regime. Such a temperature increase would, for example, require the intensity of the LISRF to be increased by a factor of 1.5, or alternatively, require the ratio of the UV-optical to IR emissivity of the dust to be increased by the same factor.

Persistent in the observations is, however, an excess of emission at wavelengths $\gtrsim 500$ μm above the calculated model spectrum. In each of the FIRAS channels the excess is only a 1 σ detection, but considering the similarity of the trend in all the $500 - 1000$ μm channels, the excess gains significance. It was previously detected in the FIRAS data by Wright et al. (1991), Reach et al. (1996), and may also be present in the residuals between the fit of a dust spectrum, characterized by a single-temperature of T=17.5 K and a ν^2 emissivity law, to an HI-correlated DIRBE and FIRAS Galactic emission spectrum (see Boulanger et al. 1996, Figure 3). The nature

of this excess emission component is still uncertain. We emphasize that this emission component should not be confused with the much stronger one found at high latitude by Reach et al. (1995), which is claimed by Puget et al. (1996) to be of extragalactic origin.

Assuming that the excess is not an instrumental effect, it should be of a Galactic origin, since it was derived by correlating the FIRAS data with a template of Galactic 100 μm emission. As a result, any extragalactic component such as the one reported by Puget et al. (1996) would not be present in this data. Several explanations have been suggested for a Galactic origin of this component (Wright et al. 1991, Wright 1993, Reach et al. 1995): (1) the excess could be due to a far-IR feature in the dust emissivity; or (2) it could be due to a Galactic population of cold ($T \approx 6\ K$) dust particles. Their low temperature is not likely the result of shielding from the interstellar radiation field, requiring enhanced dust cooling mechanisms such as expected for fractal dust grain, or needles. Recent laboratory results on the millimeter absorptivity of silicate grain materials (Agladze et al. 1996) show that the opacities of these grains is significantly larger than obtained by extrapolating the Draine-Lee values with a λ^{-2} emissivity law.

7. SUMMARY

We presented the *COBE* $3.5 - 1000$ μm spectrum of the diffuse ISM at latitudes $|b| \geq 45^o$ (Fig. 1) and showed that the near-IR intensity ratios cannot be produced by any grain size distribution of bare silicate or graphite grains (Fig. 2). In particular, we find that the 3.5-to-4.9 μm intensity ratio is consistent with PAHs being the dominant emission component at these wavelengths. We used the DIRBE data to derive an interstellar dust model that consists of PAHs and bare silicate and graphite grains, stochastically heated by the local interstellar radiation field (LISRF). In addition, we used the [C II] 158 μm line observed by the FIRAS to derive the C^+/H abundance in the diffuse high latitude ISM. The results of this paper can be briefly summarized as follows:

1) The dust model provides a very good fit to the $3.5 - 1000$ μm diffuse ISM spectrum (see Figure 3). Dust parameters are summarized in Table 3. The model requires essentially all the available Mg, Si, and Fe, and $\sim$ 15 % of the available O to be locked up in silicate grains. About 20% of the total carbon is locked up in PAHs (C/H = $(7.3 \pm 2.2)\ 10^{-5}$) and about 60-70% is locked up in graphite (C/H $\approx (2.5 \pm 0.8)\ 10^{-4}$). The abundance of PAHs in our model is higher by a factor of $\sim$2 compared to that derived in previous models of low latitude cirrus.

2) The energy radiated by the PAHs per unit H atom is $1.6\ 10^{-31}\ W/H\ atom$, and the energy absorbed from the LISRF per unit carbon atoms in PAHs is $2.6\ 10^{-27}\ W/C\ atom$. The ratio between the two quantities provides an independent estimate of the C/H ratio locked up in PAHs. The resulting value, $(C/H)_{PAH} = 6.1\ 10^{-5}$, in very good agreement with the PAH abundance required to account for the IR emission.

3) The detection of the [C II] 158 μm line by the FIRAS provides important constraints on the gas phase abundance in the cold neutral medium (CNM). We estimate the C^+/H ratio to be between $\sim (0.5 - 1)\ 10^{-4}$ (see Appenix A.3), constituting $\sim$ 10-20% of the cosmic abundance of carbon.

4) The total amount of carbon in PAHs, graphite grains, and in the gas is $C/H \sim (4.0 \pm 1.2)\ 10^{-4}$. This value is consistent with the *cosmic* carbon abundance, but barely consistent with the *interstellar medium* value of $C/H = (2.25 \pm 0.5)\ 10^{-4}$.

5) The model provides a good fit to the FIRAS spectrum in the 240 to 1000 μm wavelength regime. Detailed comparison of the residual spectrum (Figure 5) shows a systematic trend consistent with an underestimate of the interstellar dust temperature. The figure also shows the presence of an excess of emission at $\lambda \gtrsim 500$ μm above that predicted by the model. This excess emission correlates with the template of Galactic 100 μm emission, and is therefore of Galactic origin. The nature of this excess emission is still unresolved.

6) Our model provides generally a good fit to the average interstellar extinction curve (see Figure 4a). However, it produces an excess of extinction at FUV wavelengths (Fig. 4b). This excess is mainly due to the higher abundance of PAHs in the model, and the fact that we used Draine-Lee graphite particles with rising extinction in the FUV in combination with PAHs which have similar optical properties at FUV wavelengths. A fraction of the excess extinction may be real, reflecting a trend of increasing UV extinction with latitudes. The trend may be the result of an increasing PAH abundance at high Galactic latitudes.

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A. CHARACTERIZATION OF THE DUST AND PAH MOLECULES

A.1. Heat Capacities

The heat capacity plays a special role in determining the spectrum of stochastically heated particles. Small values of $C(T)$ will accelerate the cooling around T, reducing the flux emitted at the appropriate wavelengths. In contrast, large heat capacities, especially at very low temperatures, may result in an excess of long-wavelength emission.

At sufficiently high temperatures, the heat capacity of the various PAHs can be calculated

using the group additive method described by Stein, Golden, and Benson (1977; hereafter SGB). In this method, a PAH is decomposed into four carbon groups characterized by the composition of their nearest neighbors. For simplicity, we designate these atomic groups as groups $A - D$. Group A consists of the CH group in benzene (C_6H_6); group B of unsubstituted carbon in naphthalene ($C_{10}H_8$); group C is found in phenanthrene ($C_{14}H_{10}$), and group D consists of interior carbon, identical to that encountered in a monolayer of graphite . For example, chrysene ($C_{18}H_{12}$ consists of 12 members from group A, 2 from group B, and 4 from group C (it has no interior carbon atoms; see, for example, Fig. 22 of Allamandola, Tielens, & Barker (1989). The number of members from each group in a given PAH are not independent, and one can derive several simple relationships between them and $N_c \equiv N_A + N_B + N_C + N_D$, the total number of carbons in a PAH. For a fully hydrogenated PAH, the number of hydrogen atoms is given by $N_H = \sqrt{6N_c}$ (see also Omont 1986), and $N_A = N_H$ from the group definition. Empirically, we find that $N_B + N_C = N_A - 6$. To these four groups we added a group A^* to represent a dehydrogenated A group, so that $N_{A^*} = (1 - f_H)N_A$, where f_H is the number of filled hydrogen sites ($f_H = 0$ for a completely dehydrogenated PAH).

The heat capacity of a given PAH at temperature T, $C_{PAH}(T)$, is then given in the group additivity technique by the sum:

$$\begin{aligned} C_{PAH}(T) = \quad & f_H N_A C_A(T) + (1 - f_H) N_A C_{A^*}(T) + N_B C_B(T) \\ & + N_C C_C(T) + N_D C_D(T) \end{aligned} \tag{A1}$$

where the N's are the number of group members in the PAH. Following SGB, we assumed that C_C is equal to C_B, and substitution of the values of the N's in the equation for $C_{PAH}(T)$, gives for a completely hydrogenated PAH ($f_H = 1$)

$$C_{PAH}(T) = N_c \Big\{ \sqrt{\frac{6}{N_c}} \, [C_A + C_B - 2C_D] + \frac{6}{N_c} [C_D - C_B] + C_D \Big\} \tag{A2}$$

The equation shows that for sufficiently large values of N_c, the heat capacity becomes equal to the graphitic limit. The heat capacity of the various groups in the 300 to 3000 K temperature range is given by Stein (1978) and Stein & Fahr (1985). For C_{A^*} we used the heat capacity of phenyl radical [designated as $C_B - (\cdot)$ by Stein and Fahr (1985)].

The resulting values for C_A, C_B, and C_D can be written as polynomials in temperature:

$$C(J \; mole^{-1} \; K^{-1}) \; = \; \sum_{n=0}^{6} a_n T^n, \tag{A3}$$

where for C_A:
$\{a_{0-6}\} = \{-1.23, \; 4.9 \; 10^{-2}, \; 2.07 \; 10^{-5}, \; -6.93 \; 10^{-8}, \; 4.85 \; 10^{-11}, \; -1.44 \; 10^{-14}, \; 1.57 \; 10^{-18}\}$
for C_B:
$\{a_{0-6}\} = \{-7.02, \; 48.87 \; 10^{-2}, \; -1.11 \; 10^{-4}, \; 7.98 \; 10^{-8}, \; -3.33 \; 10^{-11}, \; 7.42 \; 10^{-15}, \; -6.79 \; 10^{-19}\}$

and for C_{A^*}:
$\{a_{0-6}\} = \{4.01,\ 1.62\ 10^{-2},\ 4.89\ 10^{-5},\ -1.20\ 10^{-7},\ 1.07\ 10^{-10},\ -4.41\ 10^{-14},\ 6.91\ 10^{-18}\}$

Since the group additive method breaks down at PAH temperatures below $\sim 300\ K$, the heat capacity at these temperatures was fitted with that of graphite, scaled to smoothly merge with that calculated by the group additive method. The resulting value for the heat capacity in $erg\ K^{-1}$, valid for T $\leq$ 2000 K, is given by:

$$log_{10}[C_{PAH}(T)/N_c] = -21.26 + 3.1688\ log_{10}T\ - 0.401894\ (log_{10}T)^2 \tag{A4}$$

In the limit of small carbon atoms, the PAH heat capacity reproduces tabulated values of naphtalene ($C_{10}H^8$), for which $C(T) = 8C_A(T) + 2C_B(T)$, and anthracene ($C_{14}H_{10}$), for which $C(T) = 8C_A(T) + 2C_B(T)$. For large enough PAHs, the group additive method matches the heat capacity of graphite. The value of $C_{PAH}(T)$ in eq. (A4) is essentially identical to the one presented by Puget & Léger (1989).

For graphite, the heat capacity in the $10 - 2000\ K$ temperature is given in an easily integrable form by (Markela, Volga, & Buchnev 1973):

$$C_{grf}(T) = 2.2 \times 10^7 \sum_{n=3}^{5} a_n T^n / \sum_{n=0}^{5} b_n T^n \quad [\ erg\ K^{-1} cm^{-3}] \tag{A5}$$

where the coefficients are given by: $\{a_3, a_4, a_5\} = \{0.10273,\ 4.4354\ 10^{-2},\ 2.2124\ 10^{-4}\}$, and $\{b_0, b_1, b_2, b_3, b_4, b_5\} = \{1.0003\ 10^{-12},\ 3.6909\ 10^4,\ 1129.71,\ 30.4420,\ 1.2888\ 10^{-2},\ 1.0000\ 10^{-4}\}$.

Silicate heat capacities were adopted from the values given by Draine & Anderson (1985). Silicate and graphite heat capacities were corrected by a factor of $(1 - 2/N)$, where N is the number of atoms in the grain, to take into account that the heat from photon absorption events gets only distributed in the vibrational modes of the solid (Guhathakurta & Draine 1989). No such correction was needed for the PAHs since in the small particle limit their heat capacities reproduce that of observed molecules.

A.2. Cross Sections

The cross section for graphite and silicate dust particles is given by:

$$\sigma(a, \lambda) = \pi a^2 Q(a, \lambda) \tag{A6}$$

where $Q(a, \lambda)$ is the dust absorption efficiency. Values of $Q(a, \lambda)$ were calculated from Mie theory using the dust optical constants from Draine & Lee (1984).

The PAH cross sections used in this paper were adopted from Désert, Boulanger, & Puget (1990). In their model, the PAH cross section $\sigma_{PAH}(\lambda)$ is represented by a sum of UV-visual, IR continuum, and IR line terms, as follows:

$$\sigma_{PAH}(\lambda) = \sigma_{UV-vis}(\lambda) + \sigma_{IRc}(\lambda) + \sigma_{IRl}(\lambda) \tag{A7}$$

where

$$\begin{array}{lcl} \sigma_{UV-vis}(\lambda) & = & 10^{-18} N_c \; [p_1 f_v(x) + p_2 f_u(x)] \; \mathcal{C}(\frac{x}{x_c}) \quad cm^2 \\ \sigma_{IRc}(\lambda) & = & \frac{3.3\times10^{-20}}{\lambda(\mu m)} N_c \; exp(-\frac{\lambda_m}{\lambda}) \quad cm^2 \\ \sigma_{IRl}(\lambda) & = & \sum_j \sigma_j \times exp(-\frac{(\lambda-\lambda_j)^2}{2(\Delta\lambda_j)^2}) \end{array} \tag{A8}$$

N_c is the number of C-atoms in the PAH, $x \equiv 1/\lambda(\mu m)$, $p_1 = 4.0$ and $p_2 = 1.1$ are numerical parameters, $x_c \equiv \frac{12.5}{a_{PAH}(\text{Å})}$, $a_{PAH}(\text{Å}) = 10\sqrt{N_c/120}$ is the radius of a PAH, and $\lambda_m = 10$ μm. The functions f_u, f_v, and $C(y)$ are given by:

$$\begin{array}{lcll} f_u(x) & = & (x-5.9)^2 \; (0.1x + 0.41) & \text{for } x \geq 5.9 \; \mu m^{-1} \\ & = & 0 & \text{otherwise} \\ f_v(x) & = & 1.0 & \text{for } x \geq x_l \equiv 4 \; \mu m^{-1} \\ & = & x^2 \; (3x_l - 2x)/x_l^3 & \text{for } x \leq x_l \end{array} \tag{A9}$$

$$C(y \equiv x/x_c) = \pi^{-1} \; \arctan(10^3 \; (y-1)^3/y) + 0.5 \tag{A10}$$

The last expression in eq. (A8) assumes that the PAH spectral features are Gaussian in shape. The cross section is represented as a sum over the PAH feature j, where σ_j is the value of the cross section at the line center λ_j, $\{\sigma_j/10^{-21} \; cm^2\}$=$\{35N_H, \; 4.1N_c, \; 2.9N_c, \; 3.0N_H, \; 47N_H\}$, for, respectively the 3.3, 6.2, 7.7, 8.6, and 11.3 μm bands (Léger, d'Hendecourt, & Défourneau 1989; hereafter LHD). The $\Delta\lambda_j$'s are the effective width of the j features, satisfying the condition that the integral of the cross section over the line equals $\mathcal{A}_j \equiv \lambda_j(\mu m)^2 \times f_j/1.13 \times 10^{20}$, where f_j is the dimensionless oscillator strength (LHD). The linewidths in our representations are then given by: $\Delta\lambda_j(\mu m) = 3.53 \times 10^{-17} \; f_j \lambda_j(\mu m)^2/\sigma_j(cm^2)$. The resulting values for $\Delta\lambda_j(\mu\text{m})$ are $\{0.0165, \; 0.070, \; 0.274, \; 0.157, \; 0.115\}$ at $\{\lambda_j(\mu\text{m})\}$= $\{3.3, \; 6.2, \; 7.7, \; 8.6, \; 11.3\}$, respectively. Note that our values for $\Delta\lambda_j(\mu m)$ are smaller by a factor of $\sqrt{2\pi}$ from those quoted by LHD because our choice of the functional representation of the features. The actual functional representation is irrelevant for broad band photometry (such as the DIRBE data) as long as the condition that $\mathcal{A}_j \equiv \int \sigma_j(\lambda) d\lambda$ across a feature is satisfied.

A.3. The Carbon Gas Phase Abundance in the Neutral Medium

The average high-latitude ISM spectrum calculated in the model represents the IR emission integrated over *all* gas phases along the line of sight (see eq. 1), including in addition to the H I, any high latitude molecular or ionized gas that correlates with the 100 μm emission. However, we do not expect emission from molecular gas to be a significant contributer to the IR spectrum from the average ISM gas. The high-latitude CO survey of Magnani, Blitz, & Mundy (1985) found that the surface filling factor of the high-latitude molecular gas is low, with estimates ranging from ~ 6 to 10% (see review by Magnani 1994). Rarely, molecular gas may be the dominant phase in select

cirrus clouds, with MBM 53-55 an extreme example (see Dwek, Arendt, Fixsen, D. J., & Reach 1996).

On the other hand, the warm ionized medium (WIM; a low density ionized gas that gives rise to pulsar dispersion measures, and diffuse Hα emission; e.g. Reynolds 1990), can be a significant contributor to the observed IR emission. Pulsar dispersion measures show that at high-latitudes, the $H^+/H\ I$ column densities are $\sim\ 0.2 - 0.6$ (e.g. Reynolds 1991). Assuming that the dust in the WIM is exposed to a radiation field similar to the LISRF and have a similar dust-to-gas mass ratio as in the general ISM, we get that at most one third of the observed IR intensity can originate from the ionized gas.

We therefore assume that most of the IR emission originates from the neutral medium, and that almost all of the gaseous carbon in the average high-latitude ISM is in the form of C^+, which dominates the contribution of heavy ions to the electron density. With an ionization potential of 11.26 eV it is easily ionized by the diffuse interstellar radiation field, which is not hard enough to eject a second electron. C^+ has a ground-state fine-structure line at 158 μm, which is collisionally excited by electrons, H I and H_2. The amount of gaseous C can therefore be estimated from $I(158\ \mu\mathrm{m})$ observations. The 158 μm intensity can be calculated from the FIRAS observations (see Figure 1). Subtracting the dust continuum intensity calculated by the model we derive a value of $4\pi I(158\ \mu m)/H = 1.45 \times 10^{-33}\ W/H\ atom$, a value lower by about a factor of ~ 2, compared to the $|b| \geq 15^o$ line intensity given by Bennett et al. (1994).

Most of the contribution to the observed $I(158\ \mu\mathrm{m})$ intensity comes from the neutral gas (Bennett et al. 1994), instead of the WIM. The argument presented by Bennett et al. was simple: any [C II] 158 μm emission from from the WIM will be accompanied by Hα emission. The relation between the two quantities is given by (Reynolds 1992):

$$I(158\ \mu m) \simeq 1.45 \times T_4^{0.57} (\frac{C^+/H^+}{3.3\ 10^{-3}})\ I(H\alpha) \tag{A11}$$

where

$$I(H_\alpha) \simeq 8.7 \times 10^{-11} T_4^{-0.92}\ EM \quad W\ m^{-2}\ sr^{-1} \tag{A12}$$

and where $T_4 = T/10^4\ K$, and $EM \equiv \int n_e^2 ds$ is the emission measure in units of $cm^{-6}\ pc$. Values of EM along several high latitude lines of sight are typically $\sim 1 - 2\ cm^{-6}\ pc$, giving upper limits for the $I(158\ \mu\mathrm{m})$ intensity of $\sim (2-3) \times 10^{-10}\ W\ m^{-2}\ sr^{-1}$, assuming that all the carbon is in the gas phase, and singly ionized. This intensity is significantly below the FIRAS observed value of $\sim 2 \times 10^{-9}\ W\ m^{-2}\ sr^{-1}$ (Wright et al. 1991, Bennett et al. 1994). A similar conclusion was reached by Bock et al. (1993), who derived a value of $I(158\ \mu m) \approx (9 \pm 3.5) \times 10^{-11} W\ m^{-2}\ sr^{-1}$ for the line intensity from the WIM by extrapolating the $I(158\ \mu\mathrm{m})$ versus $N_{H\ I}$ correlation to $N_{H\ I} = 0$.

Since most of the $I(158\ \mu\mathrm{m})$ emission originates from the neutral medium, we can can use the observed line intensity to derive an estimate of the $[C^+]/[H\ I]$ ratio in this medium, if the physical conditions in the medium (temperature, density, ionization state) are known. Designating

the upper and lower energy levels of the 158 μm transition as levels 2 and 1, respectively, the line intensity (in erg $s^{-1}cm^{-2}sr^{-1}$) is simply the integral of the line cooling rate along the line of sight (e.g. Osterbrock 1989), and can be written as:

$$I(\nu) = \frac{A_{21}h\nu}{4\pi} N_{C^+} (\frac{g_2}{g_1}) e^{-h\nu/kT} \frac{\sum_j (\frac{n_j}{n_{c,j}})}{1 + \sum_j (\frac{n_j}{n_{c,j}})} \tag{A13}$$

where $h\nu = 1.26\ 10^{-14} erg$ is the energy of the transition, N_{C^+} is the column density of C^+ atoms along the line of sight, $A_{21} = 2.36\ 10^{-6}\ s^{-1}$ is the Einstein A-coefficient for the $2 \rightarrow 1$ transition, $g_2 = 4$ and $g_1 = 2$ are, respectively the statistical weights of levels 2 and 1, n_j is the number density of the colliding species, and $n_{c,j} \equiv A_{21}/q_{21}$ is the critical density, where $q_{21} = 8.629\ 10^-6\ \Omega_j / g_2 T^{1/2} cm^3\ s^{-1}$ is the collisional de-excitation rate, and Ω_j is the dimensionless collision strength with species "j". For electronic collisions, $\Omega \approx 2.8$ in the $\sim$ 5000 to 20,000 K temperature interval, and $\Omega \approx 1.8$ for temperatures below $\sim 1000\ K$ (Hayes & Nussbaumer 1984). For collisions with H, $\Omega = 0.00292$ (Launay & Roueff 1977). Normalizing the observed line intensity to the observed H I-column density along the line of sight, eq (13) can be used to calculate the C^+-to-H I abundance ratio, giving:

$$\frac{[C^+]}{[H\ I]} = \frac{(g_1/g_2)\ e^{h\nu/kT}}{A_{21}h\nu}\ [\frac{4\pi I(\nu)}{N_{H\ I}}] / \sum_j (\frac{n_j}{n_{c,j}}) \tag{A14}$$

where we have made the approximation that $n_j \ll n_{c,j}$.

Most of the line emission originates from the cold neutral medium (CNM) which has typical parameters $\{n_H, T\} = \{20 - 80\ cm^{-3}, 40 - 100\ K\}$, with pressures $P/k \approx 2500\ cm^{-3}\ K$ (e.g. Heiles 1994). This medium is kept partially ionized by high-energy cosmic rays (CR). The electron density, n_e maintained by a CR ionization rate ζ_{CR} (in s^{-1}) is given by (Spitzer 1978):

$$n_e = \frac{n_i}{2}\ [1 + (1 + \frac{4\zeta_{CR}\ n_H}{\alpha^{(2)} n_i^2})^{1/2}] \tag{A15}$$

where $\alpha^{(2)} \approx 6.2\ 10^{-11}\ T^{-1/2}\ cm^3\ s^{-1}$ is the partial H$-$recombination coefficient to the n>1 levels of hydrogen, and n_i is the total number density of photo-ionized heavy elements.

Equations (A14) and (A15) can be solved for $[C^+]/[H\ I]$ as a function of the parameters of the CNM, the CR ionization rate ζ_{CR}, and the observed $I(158\mu m)/N_{H\ I}$ ratio. Estimates of ζ_{CR} range from $\approx\ 10^{-16} - 10^{-18}\ s^{-1}$. For the C^+ cooling rate per H-atom of $4\pi I(158\mu m)/N_{HI} = 1.45\ 10^{-33}\ W/H\ atom$ found earlier, and an adopted pressure of $P \approx 2000 - 3000\ cm^{-3}K$, we get a $[C^+]/[HI]$ ratio of:

$$\frac{[C^+]}{[HI]} \approx (0.5 - 1) \times 10^{-4} \tag{A16}$$

For a mean atomic weight of $\mu = 1.42$, the resulting C^+-to-gas mass ratio, $Z_{C^+} \approx (4 - 9) \times 10^{-4}$.

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Table 1. Dust Spectra/color temperatures in the Average ISM and Selected Cirrus Clouds[a]

	$I(\lambda)/I(100\ \mu\text{m})$ / T_{color} (K)		
$\lambda(\mu\text{m})$	average ISM[b]	Cloud 1[c]	Cloud 2[d]
3.3	0.00168	0.00161	0.00124
4.9	0.00252 /550	0.00074 /1500	0.00186 /500
12	0.0464 /230	0.0343 / 200	0.0600 /210
25	0.0389 /210	0.0283 / 210	0.0633 /190
60	0.160 / 70	0.114 / 70	0.178 / 75
100	1.0000 / 23	1.0000 / 44	1.000 / 24
140	1.93 / 18	2.53 / 16	2.45 / 16
240	1.28 / 19	2.51 / 16	1.36 / 21

[a]Fluxes are color-corrected and given in units of 0.7 $MJy\ sr^{-1}/N_{H\ I}(10^{20}\ cm^2)$. Numbers in parethesis in each row "j" are the color temperatures determined from the $I(\lambda_{j-1})/I(\lambda_j)$ flux ratios for a λ^{-2} dust emissvity law

[b]Fluxes represent Galactic average IR fluxes integrated over all gas phase components that spatially correlate with the observed H I emission (see §2 for more detail)

[c]average spectrum of the cloud complex MBM 53, 54, and 55 (see §2 for more details)

[d]average spectrum of cloud A (Low et al. 1984)

Table 2. Dust Model Parameters

Parameter	Value	
	Model A	Model B
PAH parameters		
N_{c1}	20	20
N_{c2}	variable	variable
γ_p	variable	variable
Z_{PAH}	variable	variable
graphite parameters	model A	model B[a]
$a_{min}(\mu\mathrm{m})$	variable	$1.29 \times 10^{-4} N_{c2}^{1/3}$
γ_1	-3.5	$3\gamma_p + 2$
$a_b(\mu\mathrm{m})$	0.1	variable
γ_2	-3.5	-3.5
$a_{max}(\mu\mathrm{m})$	0.25	0.25
Z_{grf}	variable	variable
silicate parameters		
$a_{min}(\mu\mathrm{m})$	0.0050	0.0050
γ	-3.5	-3.5
$a_{max}(\mu\mathrm{m})$	0.25	0.25
Z_{sil}	variable	variable

[a]In model B, a_{min} is calculated so that the number of carbon atoms in a spherical graphite grain of that radius is equal to N_{c2}, the number of carbon atoms in the largest PAH, and γ_1 is calculated so that $dn(N_c)/dN_c$ is continuous across a_{min}, the PAH-graphite radius boundary

Table 3. Summary of Dust Model Parameters[a]

Model Parameters[b]	Average Diffuse ISM Dust			
	Model A		Model B	
PAH				
N_{c1}	20	20	20	20
N_{c2}	100	171	100	163
γ_p	-1.67	-2.33	- 1.78	-2.67
Z_{PAH}	0.00062	0.00061	0.00060	0.00054
Graphite				
$a_{min}(\mu\mathrm{m})$	0.0005	0.0005	0.0006	0.0007
γ_1	-3.5	-3.5	—	-6.00
$a_b(\mu m)$	0.10	0.10	0.0006	0.0012
γ_2	-3.5	-3.5	-3.5	-3.5
$a_{max}(\mu m)$	0.25	0.25	0.25	0.25
Z_{grf}	0.0021	0.0020	0.0022	0.0023
Silicate				
$a_{min}(\mu m)$	0.0050	0.0050	0.0050	0.0050
γ	-3.5	-3.5	-3.5	-3.5
$a_{max}(\mu m)$	0.25	0.25	0.25	0.25
Z_{sil}	0.0053	0.0058	0.0046	0.0042
Solid Phase Abundances				
Z_{carbon}	0.0027	0.0026	0.0028	0.0028
Z_{dust}	0.0080	0.0083	0.0074	0.0070
Gas Phase Carbon Abundances[c]				
Z_{C^+}	0.0004-0.0009		0.0004-0.0009	

[a]See Table 2 for the definitions of Models A and B

[b]Dust-to-gas mass ratios are given in units of $\frac{N_H}{N_{HI}}$. For comparison, the cosmic abundances of refractory elements that can be locked up in dust are: $Z_{carbon}(\odot) = 0.0030$; $Z_{sil}(\odot) = 0.0043$ assuming a silicate composition of $\{MgSiFe\}O_4$. Elemental abundances were taken from Anders & Grevesse (1989).

[c]Calculated from the $I(158\ \mu\mathrm{m})/I(100\ \mu\mathrm{m})$ flux ratio. See Appendix A.3 for more details

Fig. 1.— The various dust spectra observed by DIRBE and FIRAS (the latter is given only for the average ISM). The average spectrum of dust in the diffuse ISM normalized at 100 μm to a flux of 0.7 $MJy\ sr^{-1}/N_{H\ I}(10^{20}\ cm^{-2})$. The other spectra have arbitrary normalizations, and are offset from the diffuse ISM spectrum for sake of clarity.

Fig. 2.— A comparison of observed intensity ratios with calculated DIRBE intensity ratios for PAHs and individual grains of various sizes and compositions. Intensity ratios for the individual PAHs were calculated as a function of N_c, the number of carbon atoms in the molecule, and for illustrative purposes converted to a radius using the relation: $a(\text{Å})=0.913\sqrt{N_c}$.

Fig. 3.— Fit of our interstellar dust model to the average dust spectrum in the diffuse ISM for model A with $N_{c2} = 100$. Details of the grain size distribution and relative abundances of the various dust components can be found in the text (§4, and Table 3).

Fig. 4.— The average extinction for the diffuse interstellar medium derived from model A with $N_{c2} = 100$ (see Table 3), is compared with the observed average interstellar extinction curve presented by Mathis (1990) renormalized to H I column densities. Detailed of the comparison are presented in the text.

Fig. 5.— Residuals of between the FIRAS average ISM spectrum and model calculations. The residuals show a trend in the $100 - 500$ μm region consistent with an underestimate in the temperature of the emitting dust. The smooth curve depicts the residuals expected with such an underestimate (see text for details). However, even with such a correction, the figure shows a persistent excess of emission at $\lambda > 500$ μm.